

Seasonal variations along auroral field lines: Measurements from the Polar spacecraft

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Abstract. Measurements from the Polar electric field instrument are used to study large electric fields and the ambient plasma density as a function of altitude ($1.8 - 6.0 R_E$ geocentric). Results from the premidnight sector (1800 – 2400 MLT) along auroral field lines show roughly a fourfold increase in the occurrence of small scale size, large amplitude electric fields ($> 100 \text{ mV m}^{-1}$) at altitudes from 1.9 to $2.5 R_E$ for dark compared to sunlit ionospheric conditions. Density values inferred from spacecraft potential measurements show these electric fields to be correlated with low plasma densities (0.2 to 3.0 cm^{-3}). An increase in the average plasma density from 10 to 60 cm^{-3} is also observed for sunlit compared to dark conditions for the same altitude range. In addition, the distribution of density measurements from 1.9 to $2.2 R_E$ also show evidence for an increase in cold ionospheric plasma (from ~ 30 to 60 cm^{-3}) for sunlit compared to dark ionospheric conditions.

1. Introduction

Auroral displays are produced by electron beams which are accelerated along terrestrial magnetic field lines that map to the auroral oval. The mechanisms in the acceleration region (from ~ 1 to $3.5 R_E$ altitude) must produce a potential drop of a few keV even though the plasma is highly conductive. As noted by *Ergun et al.* [2000] a self-consistent model of how this potential is supported or how it is distributed in altitude has not yet been established [see *Borovsky*, 1993]. In general, the density structure in the auroral zone affects both the generation of electric fields and the generation and propagation of plasma waves. Therefore, knowledge of the density structure is important in determining the validity of an acceleration model because there may be a variety of feedback mechanisms between the acceleration of particles by electric fields and the local plasma density. This article presents data from the Polar satellite which shows the correlation between the distribution of large electric fields and the magnitude of the plasma density in the acceleration region. Information such as this will provide additional insight into the causal effect between the generation of the potential drop and the ambient plasma density.

Previous observations of the plasma density which include auroral latitudes [e.g., *Persoon et al.*, 1983; *Hilgers*, 1992]

show density profiles without regard to possible seasonal variations. Observations from the Polar spacecraft have shown seasonal variations in a variety of auroral phenomena. The intensity of auroral UV images [*Liou et al.*, 1997], the occurrence probability of upgoing ion beams [*Collin et al.*, 1998], and the average plasma density at $\sim 1 R_E$ [*Johnson et al.*, 2001] all show seasonal variations. It has long been known that electric fields exist in regions of auroral particle acceleration [e.g., *Mozer et al.*, 1980]. Together, these observations indicate that there should be a consistent seasonal variation in the altitude profile of auroral electric fields, and the processes that generate them.

Recent observations by *Mozer and Hull* [2001] suggest that the existence of upward field aligned currents is a necessary but not a sufficient condition for the generation of auroral parallel potential drops. They show evidence that, in addition to field aligned currents, a low plasma density at high altitudes ($4 - 6 R_E$ geocentric) above the auroral acceleration region commonly occurs and could be necessary for the generation of the electric fields. These previous results indicate that the ambient plasma density at altitudes above $1 R_E$ in the auroral acceleration region may play an important roll in the generation of auroral electric fields. In this study the seasonal variation in the average plasma density and the occurrence of large electric fields as a function of altitude is examined.

2. Data

The Polar spacecraft was launched in 1996 into a polar orbit with perigee at $1.8 R_E$ and apogee at $9 R_E$ (geocentric) over the Northern Hemisphere. The orbit has a period of ~ 18 hours with the apogee moving equatorward at $\sim 18^\circ$ latitude per year. Precession of the orbital plane covers all local times in 6 months. The large spatial coverage of the Polar data set is obtained by using several years of data (1996 to 2001) and allows a statistical study of the altitude dependence for the processes in the auroral acceleration region. Data from the Polar electric field instrument (EFI) [*Harvey et al.*, 1995] are used to measure large electric fields. The measurements used here are in the spin plane of the spacecraft which is approximately aligned with the local meridional plane. The EFI also provides measurements of spacecraft floating potential which can be used to infer the ambient plasma density.

The spacecraft floating potential depends strongly on the electron number density and can be used as a density indicator over a wide range of electron plasma densities (less than 0.01 to over 100.0 cm^{-3}). Because the floating potential is determined by the balance of currents flowing to and from the spacecraft surface, it is also sensitive to temperature variations. A theoretical study by *Escoubet et al.* [1997] determined that solutions for densities inferred over large temperature (1 to 1000 eV) and density ranges (1 to

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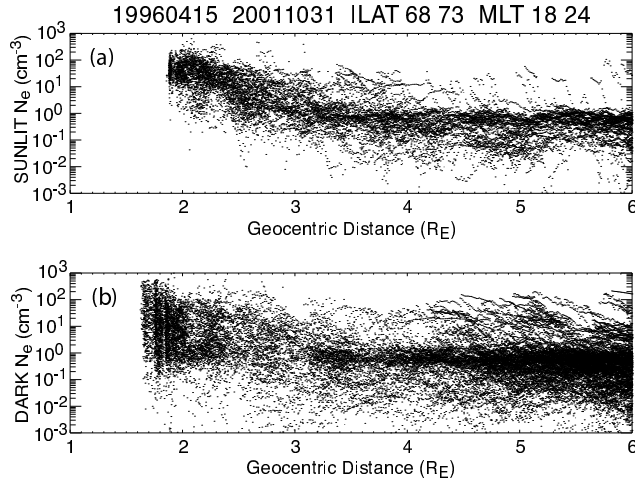


Figure 1. The distribution of the electron density inferred from the Polar spacecraft potential as a function of altitude for (a) sunlit and (b) dark ionospheric conditions.

100 cm^{-3}) will be within a factor of two from their mean. In this study, effects of high plasma temperature may lead to overestimates of the electron density under specific conditions. Observations from the FAST satellite at $\sim 4000 \text{ km}$ altitude have shown that, in the region of upflowing ion beams and accelerated downgoing electrons, the plasma density is low ($\leq 0.1 \text{ cm}^{-3}$) and is completely due to the absence of cold particles [McFadden et al., 1999b]. Although the high temperature ($\sim 1 \text{ keV}$) could result in an overestimation of the electron number density in these regions of low density,

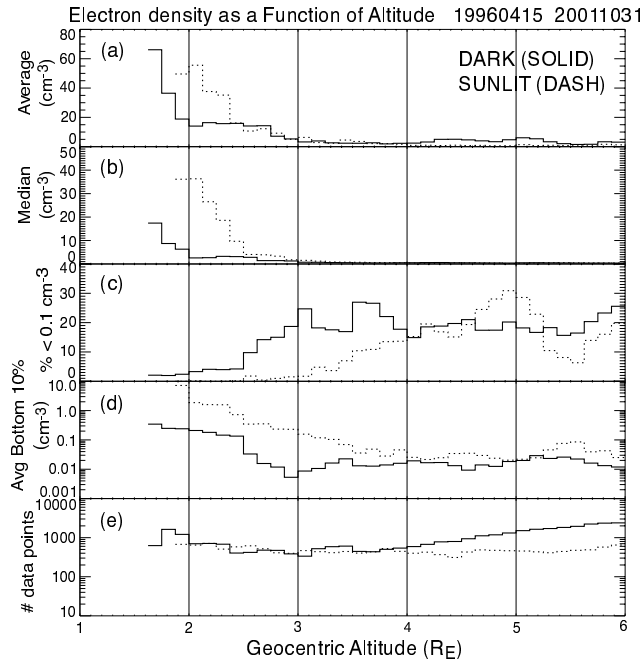


Figure 2. Inferred electron density sorted into $0.125 R_E$ bins as a function of altitude. Data are separated into sunlit (dashed) and dark (solid) ionospheric conditions. (a) The average density value. (b) The median. (c) The fraction of density measurements less than 0.1 cm^{-3} . (d) The average value of the bottom 10% of measurements. (e) The number of 30 second data points.

the inferred density values described below are consistent with the FAST results.

The data used for this study are obtained from the EFI key parameter files. In these files, large electric fields from the instantaneous electric field measurements (40 samples per second) are represented by the maximum peak to peak electric field excursion of the electric field in one spin cycle. The value used is the magnitude of the difference between the highest positive and the lowest negative electric field spikes for one spin period (~ 6 seconds). The instantaneous measurements for the resulting electric field spikes have been examined individually in order to remove those generated by noise owing to telemetry glitches and preamplifier oscillations. The spin averaged spacecraft floating potential is converted to inferred electron density values using the relationship derived by Scudder et al. [2000].

The data are then reduced to a 30 s resolution by averaging over 30 s intervals for the inferred density values and selecting the largest electric fields observed in 30 s (~ 5 spin periods) for electric fields. Data are then sorted by whether the ionosphere at the footpoint of the field line for each measurement was sunlit or dark and binned as a function of geocentric altitude. The premidnight sector (1800 to 2400 MLT) for 68° to 73° invariant latitude (ILAT) is selected for this study because this is the region of large seasonal variations in auroral UV emissions [Liou et al., 1997], ion beams [Collin et al., 1998], and density [Johnson et al., 2001].

3. Results

Figure 1 shows a scatter plot of the density measurements as a function of geocentric altitude (perigee to $6.0 R_E$) under sunlit and dark ionospheric conditions. Although there is a large scatter, the number of low density measurements increases at low altitudes ($< 3.0 R_E$) for a dark compared to a sunlit ionosphere. Under dark conditions (Figure 1b), the lowest values are frequently less than 0.1 cm^{-3} and the main band of density measurements is from 0.5 to 100 cm^{-3} . Under sunlit conditions (Figure 1a) the density rarely drops below 0.1 cm^{-3} and generally ranges from 10 to 100 cm^{-3} .

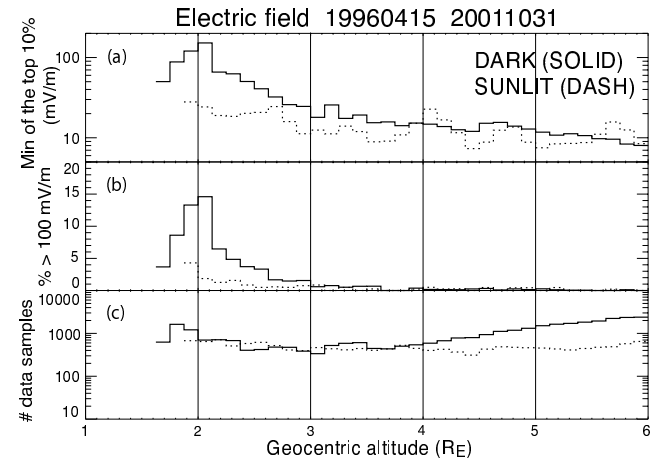


Figure 3. Measurements of electric field spikes sorted into $0.125 R_E$ bins as a function of altitude. Data are separated into sunlit (dashed) and dark (solid) ionospheric conditions. (a) The minimum of top 10% of data points. (b) The fraction of data greater than 100 mV m^{-1} . (c) The number of 30 second data points.

Figure 2 shows the results of binning the data shown in Figure 1 as a function of altitude using $0.125 R_E$ bins. Each bin contains ~ 1000 data points (Figure 2e) corresponding to 500 minutes (over 8 hours) of data per bin. There is a large increase (\sim a factor of 4) in the average density (Figure 2a) at altitudes less than $2.5 R_E$ for sunlit versus dark ionospheric conditions. The lack of low densities when the ionosphere is sunlit can also be seen in the median (Figure 2b) which increases by almost a factor of 12 for illuminated compared to dark conditions. The percent of low density measurements less than 0.1 cm^{-3} (Figure 2c) and the average of the bottom 10% of the data points in each bin (Figure 2d) show low density measurements to occur during dark conditions for altitudes up to $3.5 R_E$. Above this altitude there is no significant difference between the lowest data values for the dark and sunlit cases.

The density distributions in Figure 2 can be compared with the distribution of large electric fields shown in Figure 3. The electric field measurements are not mapped to a reference altitude assuming equipotential magnetic field lines because magnetic field-aligned electric fields exist for altitude below $3.5 R_E$ [e.g., Mozer and Hull, 2001]. The percent of the total number of electric field measurements greater than 100 mV m^{-1} in each bin (Figure 3b) is increased for altitudes between 1.9 and $2.5 R_E$ under dark versus sunlit ionospheric conditions. The minimum value of the top 10% of spikes is has a maximum $\sim 150 \text{ mV m}^{-1}$ during dark ionospheric conditions and only $\sim 25 \text{ mV m}^{-1}$ for sunlit conditions. The distribution of electric field spikes is very altitude dependent for dark ionospheric conditions whereas for sunlit conditions it is almost flat. It should be noted that for dark ionospheric conditions the maximum number of spikes greater than 100 mV m^{-1} has a similar altitude range as that of low average density. For sunlit ionospheric conditions, the same correlation is seen where there is a decrease in large electric fields present in the altitude range where there is an increase in the average density.

The above statistical analysis does not separate the low densities in the location of beams from regions where auroral acceleration is absent. To help separate these two cases, the distribution of density measurements and the occurrence of electric fields are binned as a function of density. Figure 4 shows the density and electric field distribution for altitudes which show the largest variation (from 1.9 to $2.2 R_E$). The density variations in Figure 1 are clearly seen in Figures 4b and 4d. For illuminated conditions the density distribution (Figure 4b) has a maximum at 60 cm^{-3} with few density measurements less than 5 cm^{-3} . This is compared to the distribution for dark ionospheric conditions (Figure 4d) where there is a maximum occurrence at around 30 cm^{-3} on the high density edge and remains high until falling off at $\sim 0.2 \text{ cm}^{-3}$. The maximum occurrence frequency of electric field spikes (Figure 4e) is for densities from around 0.3 to 3.0 cm^{-3} during dark ionospheric conditions. There are almost no electric field spikes during sunlit ionospheric conditions.

4. Discussion

This study has shown that large electric field spikes are most frequently observed from 1.8 (perigee) and $2.5 R_E$ altitude during dark ionospheric conditions and are almost absent for sunlit conditions. In the same altitude range, the average plasma density is also strongly dependent on the illumination of the ionosphere and has much lower (\sim a factor of 4) densities for darkness. At higher altitudes (above 2.5

R_E), the figures show no clear dependence of the electric field occurrence and the average plasma density on ionospheric illumination. There is, however, an increase in the occurrence of low density measurements for altitudes below $3.5 R_E$ under dark ionospheric conditions (Figure 2c).

Density depletions have long been observed in regions of ion beams, large electric fields, and accelerated auroral electrons [e.g., Mozer *et al.*, 1980]. Our observations of large electric fields and regions of decreased average density are consistent with these earlier observations. As expected, the low density measurements in Figure 2 are in agreement with the seasonal variations in average densities and indications of small scale, low density regions ($\sim 1 R_E$ altitude) observed by [Johnson *et al.*, 2001]. In addition, the low densities correlate with an increase in the occurrence of up flowing ion beams [Collin *et al.*, 1998] and an increase in the intensity of auroral UV emissions [Liou *et al.*, 1997]. The observations of low densities and large electric fields during dark ionospheric conditions (Figures 2 and 3) are consistent with the location of large electric fields observed using measurements from the Polar [Mozer and Hull, 2001] and, at the low end of our measurements, the FAST [McFadden *et al.*, 1999a] satellites. They also support earlier observations which show large amplitude electric fields to exist at altitudes above 5000 km [e.g., Weimer *et al.*, 1985].

Results presented here indicate that large electric fields at these altitudes occur predominantly at low density values (0.3 to 3.0 cm^{-3}) during dark ionospheric conditions. These density measurements match those reported by McFadden *et al.* [1999b] who find evidence that all cold ionospheric plasma ($< 30 \text{ eV}$) is absent from auroral cavities having plasma densities from ~ 0.2 to 2.0 cm^{-3} . The remaining plasma in these depletions is hot ($\sim 1 \text{ keV}$) compared to the

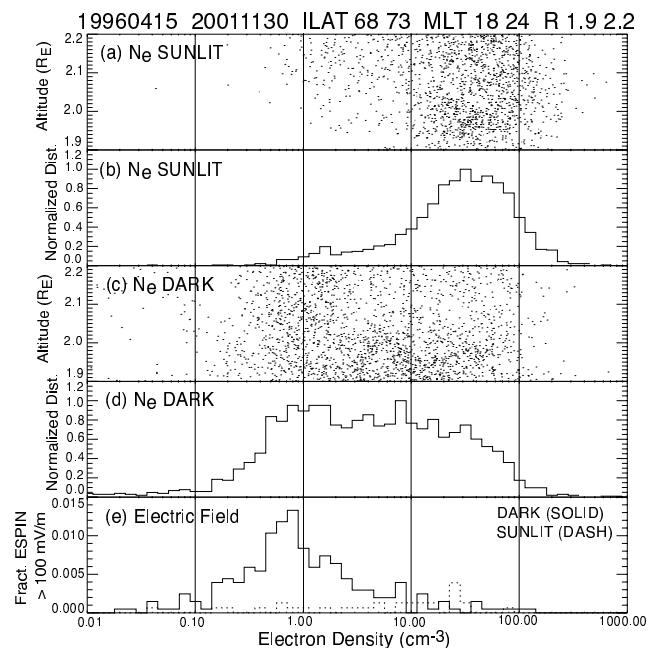


Figure 4. The distribution of the inferred density and the occurrence of electric field spikes for 1.9 to $2.2 R_E$ geocentric altitude. (a – d) The location in altitude and binned distribution of the density values for sunlit and dark conditions. (e) The fraction of electric field measurements greater than 100 mV m^{-1} for sunlit (dashed) and dark (solid) conditions.

cold ionospheric plasma. Our measurements indicate that the effect of the plasma temperature on the inferred densities is not visible to the accuracy of this study. Together with the results herein, this shows evidence for a clear increase in the presence of low density measurements and electric fields for dark ionospheric conditions for altitudes from 1.9 to 2.5 R_E .

The results presented here also indicate that for illuminated conditions (at $\sim 2 R_E$ geocentric) there is an increase in the density of cold ionospheric plasma which corresponds to a decrease in the occurrence of large electric fields (Figure 4e). The location of the highest measurements in the density distribution (Figures 4b and 4d) increases by a factor of ~ 2 for sunlit compared to dark conditions (with the plateau reached at $\sim 60 \text{ cm}^{-3}$ and 30 cm^{-3} , respectively). This density variation may be due to the change in the ambient background density and is related to the mechanisms responsible for auroral acceleration. Freja data at lower altitudes (1400–1770 km) [Karlsson and Marklund, 1996] shows large electric field events ($> 200 \text{ mV m}^{-1}$) to have the greatest occurrence for high ionospheric conductivities inferred from the solar zenith angle. The results presented here show a similar variation but show a correlation between density variations at higher altitudes ($> 1 R_E$) and the occurrence of electric fields.

Two possible interpretations of the observed electric fields are electrostatic structures [e.g., Mozer *et al.*, 1980] or electric fields resulting from Alfvén waves [Song and Lysak, 2001]. The ambient plasma density from which the electric fields form is important in both of these interpretations because it affects both the ability of the plasma to conduct currents [Ergun *et al.*, 2000] and the altitude of the maximum drift velocity of electrons [e.g., Lysak and Hudson, 1979]. Density measurements presented herein are useful in determining the importance of these models because the mapping of recent electric field measurements from Polar (4–7 R_E geocentric) are consistent with both Alfvén wave and electrostatic structures [Keiling *et al.*, 2001].

In summary, the results presented herein show large seasonal variations in the altitude profile of the occurrence of auroral electric fields and density cavities. In particular, they show that decreases in plasma density are strongly correlated with the existence of large electric fields. There is also evidence that there is an associated variation in the plasma densities outside density cavities at these altitudes. Density profiles in the auroral acceleration region show large altitude variations in the average density and occurrence of electric field spikes at altitudes less than 2.5 R_E geocentric. These observations are consistent with the existence of large electric field at the bottom of the auroral acceleration region. In addition, the results presented here show a clear seasonal variation the existence of the electric fields and density depletions correlated to variations in the illumination of the ionosphere. Large electric fields and plasma depletions occur mainly during dark ionospheric conditions. The density values correlated with large electric fields agree with measurements that indicate the lack of cold plasma in regions of field aligned acceleration.

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